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From Heat Ingress to Financial Haemorrhage: Thermodynamic Characterization and Boil-Off Gas Economics of an LPG Storage Tank Under Tropical Ambient Conditions

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Abstract

The generation of boil-off gas (BOG) in liquefied petroleum gas (LPG) storage tanks represents a simultaneous safety hazard and an escalating economic drain—especially within emerging tropical markets where ambient temperatures remain persistently elevated throughout the year. This study presents a comprehensive thermodynamic and heat-transfer analysis of a commercial 62.296 m³ double-containment, perlite-insulated LPG storage tank in Port Harcourt, Nigeria, characterized by a 12-month dataset of tank temperature and pressure. The Peng-Robinson equation of state is employed to compute monthly specific volume, density, compressibility factor, entropy, and enthalpy of butane LPG across ambient temperatures ranging from 297.1 K to 300.4 K. Thermal resistance analysis yields a total cylindrical wall resistance of 0.211 mK/W and a hemispherical end-cap resistance of 1.7738 m²K/W, confirming the dominant role of perlite insulation in impeding heat ingress. Monthly total heat leakage varies between 1,806.4 W (July) and 2,396.3 W (February), directly modulating BOG generation. The BOG rate ranges from 0.00666 kg/s to 0.00877 kg/s, with daily BOG quantities of 2.56%–3.26% of tank volume. At the prevailing LPG market price of ₦850/kg, the resulting financial losses span ₦5.66 to ₦7.45 per second of storage—equivalent to annual losses of up to ₦235 million per tank from heat-induced vapour generation alone. A strong positive linear correlation between ambient temperature and BOG generation is demonstrated, providing an analytical basis for targeted insulation upgrade and BOG recovery investment decisions in the Nigerian LPG sector.

Keywords: Boil-off gas; Energy losses; LPG storage; Peng-Robinson EOS; Thermal resistance; Thermodynamic properties; Tropical climate.

INTRODUCTION

Liquefied petroleum gas (LPG) is a critical energy vector in Nigeria and across the developing world, serving domestic cooking, transportation, and industrial heating needs. The Nigerian government's National LPG Expansion Plan has catalysed the rapid proliferation of skid-mounted LPG storage facilities, yet this growth has outpaced the deployment of boil-off gas (BOG) mitigation and recovery infrastructure (NLPGEP, 2022). BOG is the continuously vaporised LPG generated when heat from the environment leaks through the tank wall and raises the internal temperature above the local saturation point, increasing tank pressure and permanently altering LPG composition over time (Dobrota *et al.*, 2013).

In tropical locations such as Port Harcourt (latitude ~4.8°N), the temperature differential between stored LPG (~289–291 K) and ambient air (297–300 K) persists year-round, sustaining a continuous and substantial heat flux into storage tanks (Amadi, 2018). Unlike cryogenic LNG systems, where BOG has been extensively modelled (Chen *et al.*, 2004; Khan *et al.*, 2020), LPG storage under tropical conditions remains comparatively under-studied, particularly with respect to the coupled thermodynamic–financial analysis needed to drive infrastructure investment decisions.

This paper addresses that gap by performing a rigorous, month-by-month evaluation of:

- all relevant thermodynamic state properties of butane LPG using the Peng-Robinson equation of state (PR-EOS);
- conductive and convective thermal resistance of a commercially operated double-containment tank;
- heat leakage through cylindrical and hemispherical tank sections; and
- BOG generation rates and their direct financial cost equivalents.

The analysis uses 12 months of operational logbook data from a Banner Energy / Kada Technology (KTL, 2019) LPG storage tank and a MATLAB numerical implementation for reproducibility.

RELATED WORK

Khelifi *et al.* (2010) pioneered the coupled thermodynamic and heat-transfer simulation of LNG cryogenic tanks, demonstrating that pressure buildup is sensitive to tank geometry and insulation thermal conductivity. Khelifi *et al.* (2010) employed two-dimensional numerical methods to study natural convection in LNG tanks, finding that the Rayleigh number governs heat transfer intensity and that the evaporative flux is maximum near the tank wall. These foundations underpin the approach adopted in the present study.

For LPG specifically, Zakaria *et al.* (2006) presented comprehensive heat and mass transfer studies in LPG storage, establishing that the saturation-temperature coupling means even modest heat ingress drives measurable vapour generation. Shamekhi and Ashouri (2021) quantified BOG losses in LPG tanks and proposed insulation thickness guidelines, but did not evaluate thermodynamic property variation using a cubic EOS. Gbaarabe and Sodiki (2023) quantified the economic implications of BOG in the Nigerian LPG supply chain, providing the financial unit cost model adopted herein. Adom *et al.* (2010) developed the BOG rate formulation based on total heat leakage and enthalpy change, which is the core formula of the present analysis.

Table 1: Technical parameters of the LPG storage tank.

Parameter	Value
Tank total length, L	10.0 m
Cylindrical shell length, l	7.4 m
Internal diameter, d	2.6 m (r _o = 1.3 m)
Capacity	62.296 m ³
Shell/end-cap thickness	14 mm (each)
Insulation thickness	250 mm (perlite)
Outer radius, r ₃	1.578 m
Tank material	Carbon steel Q345R
Insulation material	Perlite (vacuum annulus)
Fill level	85% of capacity (52.95 m ³)

More recent work by Al Ghafri *et al.* (2021) applied advanced BOG prediction models to full-containment LNG tanks, demonstrating that static boil-off rate is strongly geometry-dependent and that insulation performance declines non-linearly with ambient temperature. The present contribution extends these methodologies to a tropical butane LPG context, filling a geographic and compositional gap in the published literature.

SYSTEM DESCRIPTION AND METHODOLOGY

Storage Tank and Data Acquisition

The case study tank is a commercial double-containment steel-in-steel cylindrical vessel with hemispherical end-caps, manufactured by Kada Technology Ltd. (KTL, 2019) and operated by Banner Energy, Port Harcourt. Key geometric and material parameters are given in Table 1. The inner shell and end-cap are Q345R carbon steel (k₁ = k₃ = 51.5 W/mK); the annular insulation is perlite (k₂ = 0.95 W/mK), and the vacuum annulus provides negligible additional conduction

Table 2: Summary of monthly thermodynamic properties of LPG in the storage tank.

Month	T _a (K)	T ^{LNN} (K)	Z	v (m ³ /kg)	ρ (kg/m ³)	Δs (kJ/kgK)	Δh (kJ/kg)
January	300.2	289.8	0.8630	0.001704	587.04	0.4340	125.96
February	300.4	291.0	0.9413	0.001700	588.30	0.4571	133.24
March	300.1	290.5	0.9020	0.001701	587.77	0.4475	130.19
April	299.8	289.8	0.8630	0.001704	587.04	0.4340	125.96
May	299.2	289.5	0.8228	0.001704	586.72	0.4282	124.14
June	298.1	289.2	0.7825	0.001705	586.41	0.4225	122.32
July	297.1	289.0	0.7418	0.001706	586.20	0.4186	121.11
August	297.1	289.0	0.7418	0.001706	586.20	0.4186	121.11
September	297.7	289.0	0.7418	0.001706	586.20	0.4186	121.11
October	298.2	289.5	0.8228	0.001704	586.72	0.4282	124.14
November	298.9	289.5	0.8228	0.001704	586.72	0.4282	124.14
December	299.8	289.8	0.8631	0.001703	587.03	0.4340	125.96

resistance. Daily temperature and pressure data were recorded from the PAVAN supervisory interface; monthly averages are presented in Table 2.

Thermodynamic Property Determination (PR-EOS)

The Peng-Robinson equation of state is used to determine the specific molar volume \tilde{v} of butane LPG (treated as 100% n-butane; $T^c = 425.16$ K; $P^c = 3,796,000$ N/m²; $M = 58.12$ kg/kmol; $R = 8.3145$ J/molK) (Cengel *et al.*, 2019):

$$P = RT / (\tilde{v} - b) - a / [\tilde{v}(\tilde{v} + b) + b(\tilde{v} - b)] \quad (1)$$

where the constants are: $a \approx 2.3518$ Pa·m⁶/mol², $b \approx 3.4541 \times 10^{-3}$ m³/mol, and c (repulsive correction) $\approx -2.0531 \times 10^{-7}$ Pa·m⁶/mol². Solving the resulting cubic equation in \tilde{v} gives three roots; for liquid-phase LPG, the smallest physically meaningful root is selected (Usman, 2016). Mass density and specific volume follow directly:

$$\rho = M / \tilde{v}^{NTOL}; \quad v = 1/\rho \quad (2)$$

The compressibility factor Z is obtained from:

$$Z = P\tilde{v} / (RT) \quad (3)$$

Entropy change from a reference state is decomposed into ideal-gas and residual contributions (Moran *et al.*, 2011):

$$\Delta S = \Delta S^{ID} + \Delta S^{res} = C_p \ln(T/T_0) - R \ln(P/P_0) + \Delta S^{res} \quad (4)$$

and enthalpy change from:

$$\Delta h = T\Delta s + v(P - P_0) \quad (5)$$

Thermal Resistance Analysis

The storage tank wall comprises three concentric layers (inner steel, perlite, outer steel) for both the cylindrical barrel and hemispherical end-caps. The conduction resistances are (Bergman *et al.*, 2011):

$$R^{cond, cy} = \sum \ln(r_{i+1}/r_i) / (2\pi k_i l) \quad (6)$$

$$R^{cond, sh} = \sum (1/r_i - 1/r_{i+1}) / (4\pi k_i) \quad (7)$$

Convective resistances at the inner (LPG–wall) and outer (wall–air) surfaces of the cylindrical and hemispherical sections are:

$$R^{conv, cy} = 1/(h^{LNN} \cdot 2\pi r_0 l) + 1/(h_{air}^r \cdot 2\pi r_3 l) \quad (8)$$

$$R^{conv, sh} = 1/(h^{LNN} \cdot 4\pi r_0^2) + 1/(h_{air}^r \cdot 4\pi r_3^2) \quad (9)$$

The convective coefficient of the LPG under natural convection ($Gr = -4.2315 \times 10^{16}$; stable stratification) is $h^{LNN} = 6861$ W/m²K, and for forced convection of ambient air ($Re_{air}^r = 147,659,115$; $x_{air}^r = 2.32$ m/s) $h_{air}^r = 14.056$ W/m²K. The total thermal resistances are:

$$R_{i,ta}^{o,L, cy} = R^{cond, cy} + R^{conv, cy} = 0.211 \text{ mK/W} \quad (10)$$

$$R_{i,ta}^{o,L, sh} = R^{cond, sh} + R^{conv, sh} = 1.7738 \text{ m}^2\text{K/W} \quad (11)$$

Heat Leakage and BOG Quantification

Monthly heat leakage through the cylindrical shell and hemispherical end-caps are, respectively as (Bergman *et al.*, 2011):

$$q^{cy} = 2\pi l(T_0 - T) / R_{i,ta}^{o,L, cy} \quad (12)$$

$$q^{sh} = 4\pi(T_0 - T) / R_{i,ta}^{o,L, sh} \quad (13)$$

$$Q_{i,ta}^{o,L} = q^{cy} + 2q^{sh} \quad (14)$$

The BOG quantity (% of liquid volume per day), generation rate (kg/s), and cost equivalent of loss (₦/s) are (Adom *et al.*, 2010; Gbaarabe and Sodiki, 2023):

$$Q^{BAG} = (Q_{i,ta}^{o,L} / (\rho \times \Delta h \times V)) \times 86400 \times 100\% \quad (15)$$

$$R^{BAG} = Q_{i,ta}^{o,L} / \Delta h \quad (16)$$

$$c_u^e = R^{BAG} \times C \quad (17)$$

where $C = \text{₦}850/\text{kg}$ is the prevailing domestic LPG retail price in Port Harcourt.

RESULTS AND DISCUSSION

Thermodynamic State Properties of LPG

Table 2 summarises the computed thermodynamic properties for all 12 months derived from the PR-EOS and monthly-averaged logbook data. The ambient temperature ranged from 297.1 K (July, August) to 300.4 K (February), while LPG temperature varied over a narrow band of 289.0–291.0 K, reflecting the thermal buffering role of the perlite insulation.

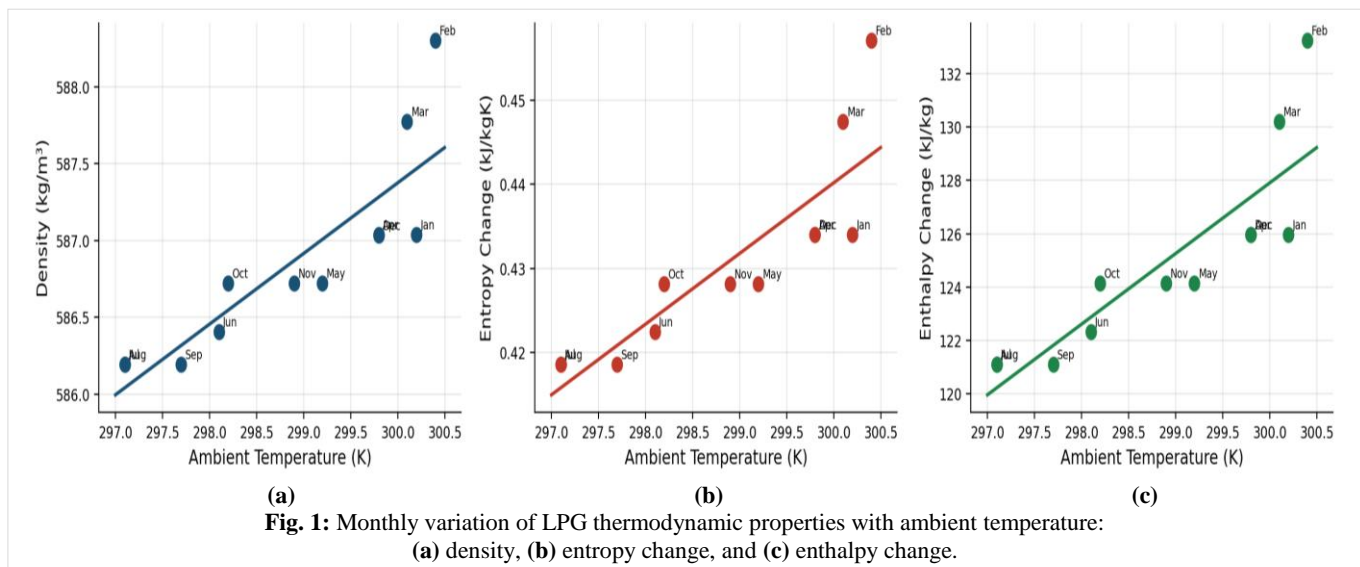


Fig. 1: Monthly variation of LPG thermodynamic properties with ambient temperature: (a) density, (b) entropy change, and (c) enthalpy change.

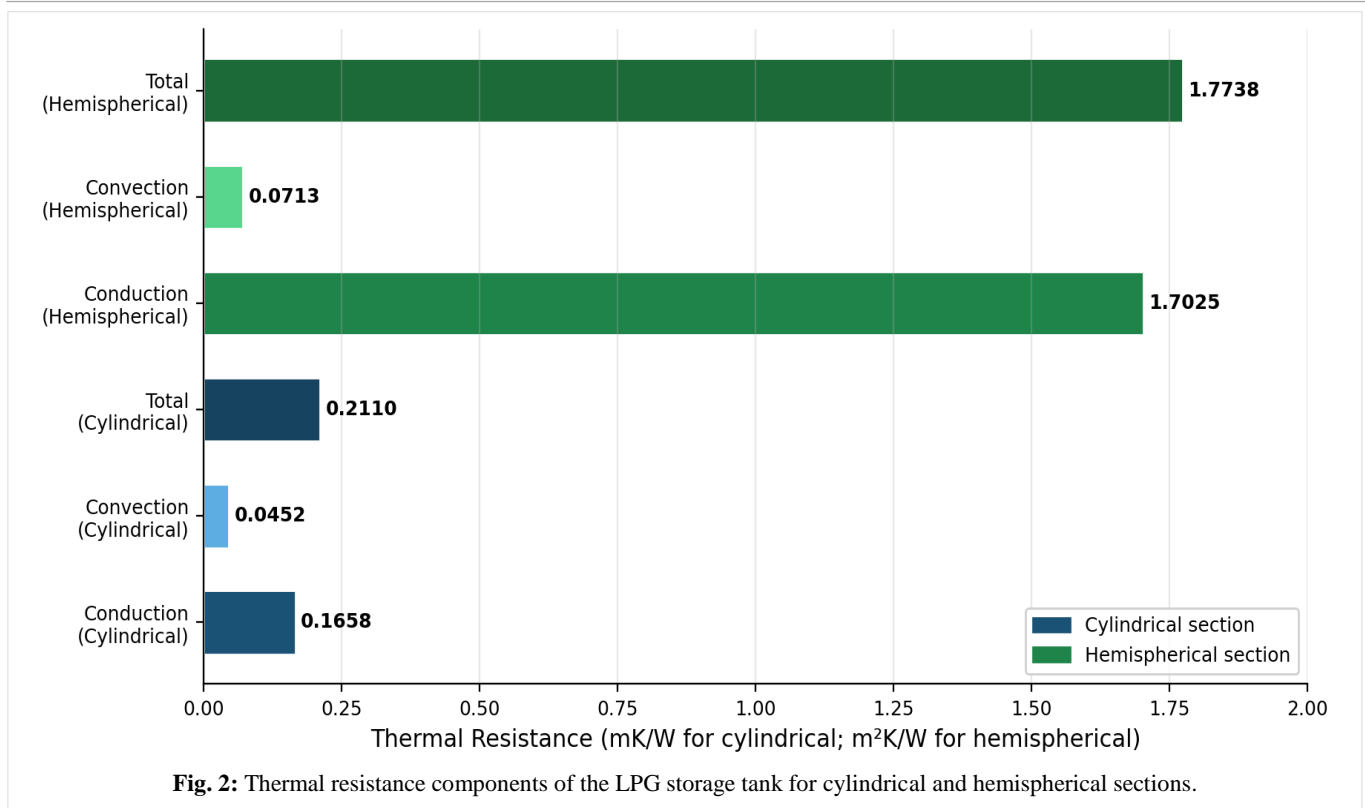


Fig. 2: Thermal resistance components of the LPG storage tank for cylindrical and hemispherical sections.

The density of liquid butane varies between 586.20 and 588.30 kg/m³, exhibiting a positive correlation with both LPG temperature and compressibility factor. The compressibility factor Z ranged from 0.7418 to 0.9413, indicating substantial deviation from ideal-gas behaviour—underscoring the necessity of a real-gas EOS for accurate property determination. Fig. 1 illustrates the variation of density, entropy, and enthalpy with ambient temperature, all showing clear monotonic increase with rising ambient conditions.

The entropy change peaked at 0.4571 kJ/kgK in February (highest ambient temperature) and was lowest at 0.4186 kJ/kgK during July–September. Similarly, the enthalpy change was maximal in February at 133.24 kJ/kg and minimal in July at 121.11 kJ/kg. These values directly govern BOG generation via Eq. (16): a higher Δh in cooler months partially offsets the effect of greater heat ingress in hotter months, creating a non-linear coupling that the simplified BOG models in prior literature often neglect.

Thermal Resistance of the Storage Tank

Fig. 2 presents the thermal resistance breakdown across both tank sections. The conductive resistance of the cylindrical section is $R_{cond,cy} = 0.1658$ mK/W, dominated by the 250 mm perlite layer whose conductivity (0.95 W/mK) is 54 times lower than the steel shell. The convective resistance of 0.0452 mK/W is comparatively small, confirming that insulation quality—not surface heat transfer—is the controlling resistance in this system.

For the hemispherical end-caps, $R_{cond,sh} = 1.7025$ m²K/W, which is 10.3 times greater than the cylindrical conduction resistance, primarily due to the spherical geometry factor in Eq. (7). The total hemispherical resistance $R_{ta}^{oL,sh} = 1.7738$ m²K/W is 8.4 times higher than the cylindrical total

(0.211 mK/W). This geometry-driven asymmetry means that, despite two hemispherical caps accounting for a smaller surface area than the cylindrical barrel, their superior insulating performance is a significant design advantage. Any degradation of the spherical cap insulation would disproportionately increase overall heat leakage.

Monthly Heat Leakage

Fig. 3 presents the monthly heat leakage decomposed into cylindrical and hemispherical contributions. The cylindrical shell accounts for 93.4–94.6% of total heat leakage in all months, reflecting its larger surface area and lower resistance. Monthly total heat leakage ranged from 1,806.4 W in July/August (coolest ambient temperatures) to a peak of 2,396.3 W in February (warmest month), a seasonal variation of 32.6%.

Table 3 summarises the full heat leakage results. The February peak can be attributed to the simultaneous maximum ambient temperature (300.4 K) and maximum ΔT = 9.4 K driving force. Notably, the hemispherical contribution ranges from 98.3 W (July) to 126.2 W (January), exhibiting smaller absolute variation than the cylindrical component because the reduced surface area limits total heat flux even as the temperature differential changes. These findings align with the stratification analysis of Khelifi *et al.* (2010), who showed that natural convection amplification of heat flux is most pronounced at elevated Rayleigh numbers corresponding to hotter ambient conditions.

BOG Generation and Economic Impact

Fig. 4 demonstrates the positive linear correlation between ambient temperature and BOG generation rate. As ambient temperature increases from 297.1 K to 300.4 K, the BOG rate

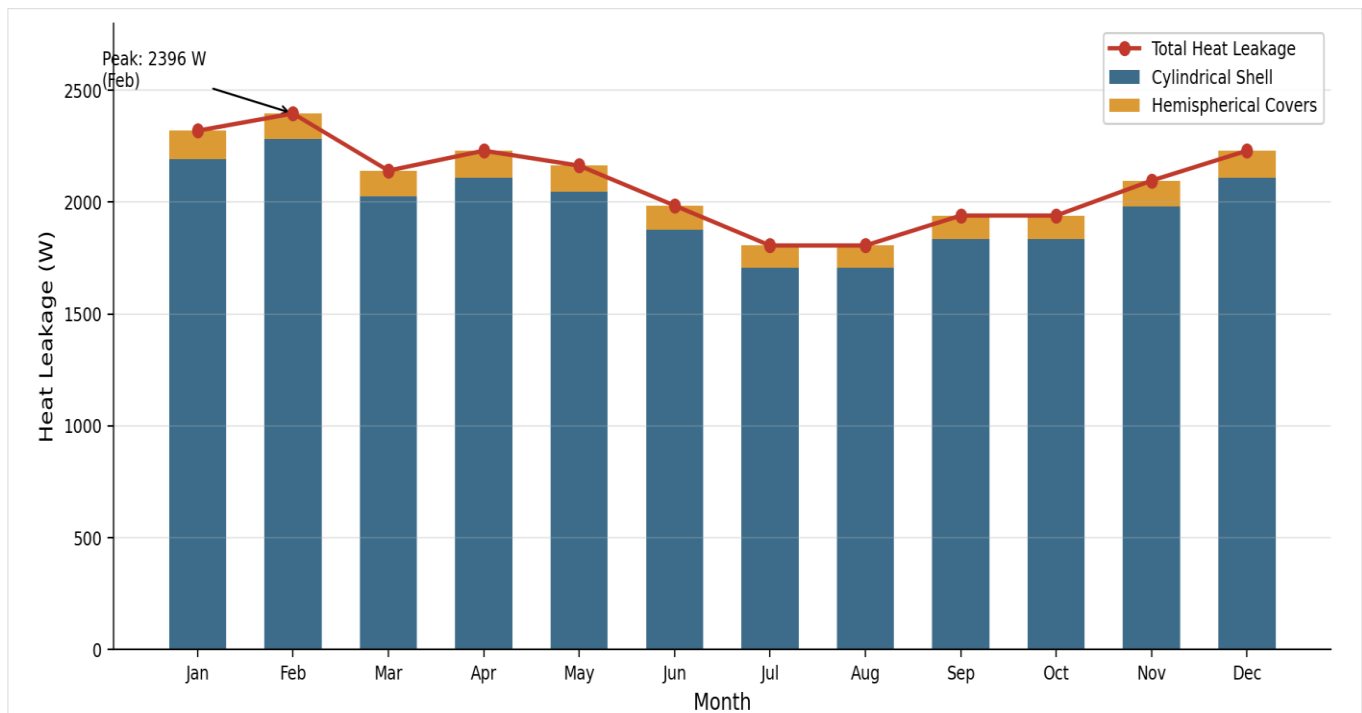


Fig. 3: Monthly heat leakage through the LPG storage tank decomposed into cylindrical shell and hemispherical end-cap contributions.

Table 3: Summary of monthly heat Leakage through the LPG storage tank.

Month	T _a (K)	T _{LNN} (K)	ΔT (K)	q _{cyl} (W)	q _{hemi} (W)	Q _{total} (W)
January	300.2	289.8	10.4	2193.19	126.19	2319.38
February	300.4	291.0	9.4	2282.27	114.06	2396.33
March	300.1	290.5	9.6	2024.45	116.48	2140.93
April	299.8	289.8	10.0	2108.80	121.34	2230.14
May	299.2	289.5	9.7	2045.54	117.70	2163.24
June	298.1	289.2	8.9	1876.83	107.99	1984.82
July	297.1	289.0	8.1	1708.13	98.28	1806.41
August	297.1	289.0	8.1	1708.13	98.28	1806.41
September	297.7	289.0	8.7	1834.66	105.56	1940.22
October	298.2	289.5	8.7	1834.66	105.56	1940.22
November	298.9	289.5	9.4	1982.27	114.06	2096.33
December	299.8	289.8	10.0	2108.80	121.34	2230.14

increases from 0.00666 to 0.00877 kg/s—a 31.7% rise over a 3.3 K ambient temperature range. This steep sensitivity underscores the vulnerability of tropical LPG storage to even modest seasonal warming, consistent with the findings of Shamekhi and Ashouri (2021).

Fig. 5 quantifies the financial haemorrhage. The linear relationship between BOG rate and cost equivalent of lost LPG ($R^2 = 1.000$) confirms that every incremental 1×10^{-3} kg/s increase in BOG rate translates to an additional ₦0.85/s of economic loss (at $C = ₦850/\text{kg}$). Monthly peak losses reach ₦7.45/s (February), equivalent to ₦644 k/day or approximately ₦235 M/year per tank.

Table 4 presents the full annual BOG and financial results.

Cumulatively, the 12-month analysis projects an annual BOG-equivalent financial loss of approximately ₦215–235 million per tank from heat-induced vapourisation alone. This figure excludes pipeline fugitive losses, piston-effect displacement, and pump dissipation sources (Dobrota *et al.*, 2013), suggesting the true supply-chain loss is substantially higher. In a market with hundreds of unregulated skid plants of similar capacity, the aggregate national economic impact is considerable and provides a compelling case for mandatory BOG recovery system installation.

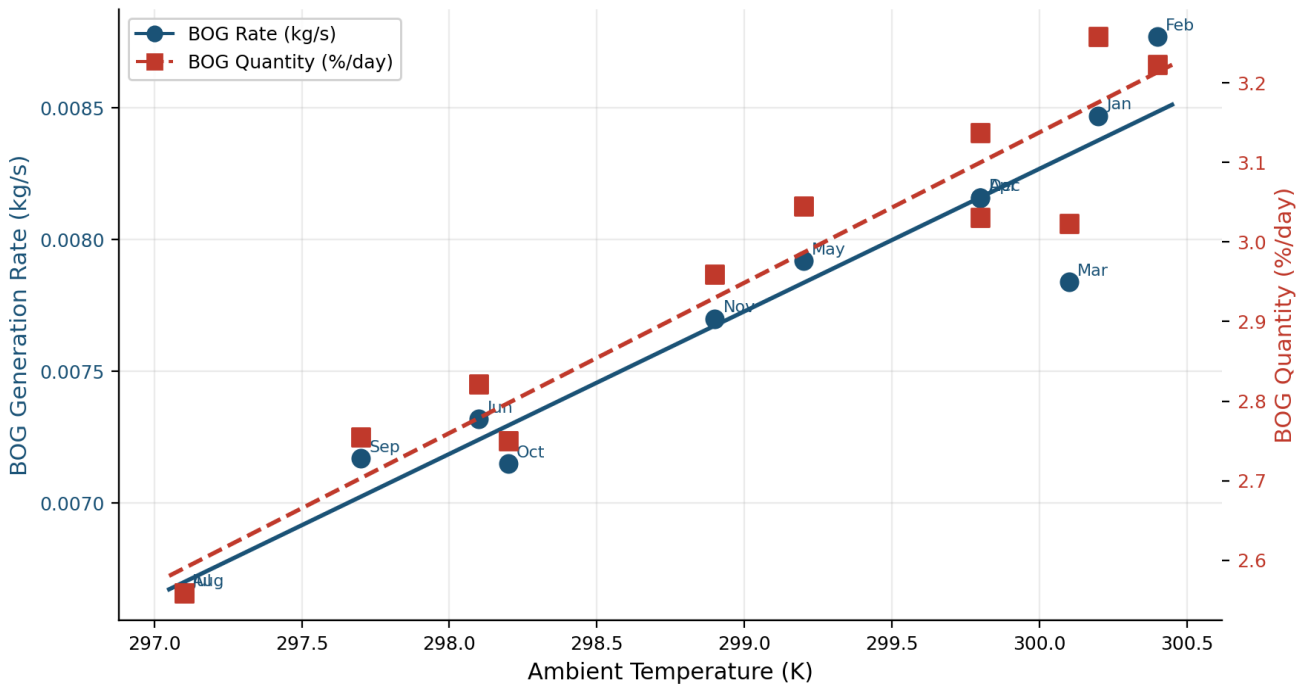


Fig. 4: Positive linear correlation between ambient temperature and both BOG generation rate (kg/s) and BOG quantity (%/day) across 12 months.

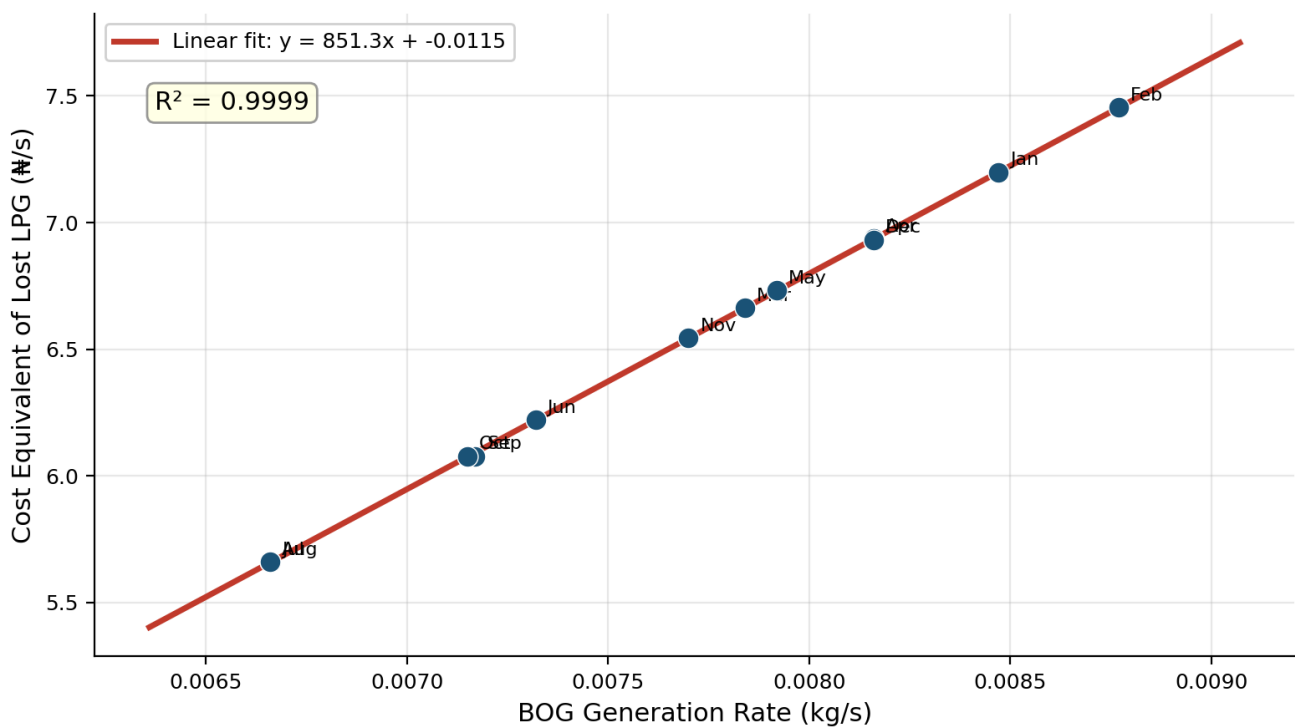


Fig. 5: Linear relationship between BOG generation rate and cost equivalent of lost LPG, demonstrating a near-perfect proportional relationship ($R^2 = 1.000$).

CONCLUSION

This study has provided a rigorous, data-driven characterisation of heat-induced thermodynamic degradation and its economic consequences in a tropical LPG storage tank. The key findings are:

- 1) All thermodynamic properties of butane LPG (density, compressibility factor, entropy, enthalpy) are systematically sensitive to ambient temperature; the PR-EOS provides an accurate and computationally tractable model for their monthly computation from plant logbook data.

Table 4: Summary of BOG Generation and Cost Equivalent of Lost LPG ($C = \text{₦}850/\text{kg}$).

Month	T_a (K)	Q _{total} (W)	BOG Qty (%/day)	BOG Rate (kg/s)	Cost Eq. (₦/s)	Cost Eq. (₦/day)
January	300.2	2319.38	3.258	0.00847	7.20	622,080
February	300.4	2396.33	3.224	0.00877	7.45	643,680
March	300.1	2140.93	3.023	0.00784	6.66	575,424
April	299.8	2230.14	3.031	0.00816	6.94	599,616
May	299.2	2163.24	3.046	0.00792	6.73	581,472
June	298.1	1984.82	2.821	0.00732	6.22	537,408
July	297.1	1806.41	2.559	0.00666	5.66	489,024
August	297.1	1806.41	2.559	0.00666	5.66	489,024
September	297.7	1940.22	2.755	0.00717	6.08	525,312
October	298.2	1940.22	2.750	0.00715	6.08	525,312
November	298.9	2096.33	2.959	0.00770	6.55	566,100
December	299.8	2230.14	3.137	0.00816	6.93	598,752

- 2) The total thermal resistance of the cylindrical tank wall (0.211 mK/W) is dominated by the perlite insulation layer (94.1% of conduction resistance), while the hemispherical end-caps exhibit 8.4× higher total resistance due to their spherical geometry—an important design consideration for future tank geometries.
- 3) Monthly total heat leakage ranges from 1,806 W to 2,396 W, driven by the positive correlation between ambient temperature and temperature differential ΔT , with February representing peak heat stress.
- 4) BOG generation rate spans 0.00666–0.00877 kg/s across the year, corresponding to daily BOG quantities of 2.56–3.26% of tank volume. The linear relationship between ambient temperature and BOG rate quantified here provides an analytical basis for predictive BOG management.
- 5) The financial loss from heat-induced BOG ranges from ₦5.66 to ₦7.45/s, projecting to ₦215–235 million annually per tank—a compelling economic argument for insulation maintenance and BOG recovery system installation in Nigerian LPG facilities.

Future work should incorporate solar radiation and wind speed effects on outer-surface convection, extend the analysis to propane–butane blends at varying compositions, and evaluate the economics of vapour-compression BOG recovery against the loss quantified here.

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The present research did not receive any financial support to conduct the research.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent,

misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

REFERENCES

- 1) NLPGEP (2022) *LPG Value Chain*. National LPG Expansion Plan. Available at : <http://dlpgovp.org/lpg-value-chain>
- 2) Dobrota, D., Lalic, B. and Komar, I. (2013) ‘Problem of boil-off in LNG supply chain’, *Trans. Marit. Sci.*, 2(2), pp. 91–100.
- 3) Amadi, H.N. (2018) ‘Wind energy potential assessment of coastal states in South-South Nigeria based on the Weibull distribution model’, *Eur. J. Elect. Eng. Comput. Sci.*, 2(7), pp. 1–6.
- 4) Chen, Q.S., Wegrzyn, J. and Prasad, V. (2004) ‘Analysis of temperature and pressure changes in liquefied natural gas (LNG) cryogenic tanks’, *Cryogenics*, 44(10), pp. 701–709.
- 5) Khan, M.S., Qyyum, M.A., Ali, W., *et al.* (2020) ‘Energy saving through efficient BOG prediction and impact of static boil-off-rate in full containment-type LNG storage tank’, *Energies*, 13(7), pp. 1–14.
- 6) Khelifi, M.S., Benbrik, A., Lemonnier, D., *et al.* (2010) ‘Laminar natural convection flow in a cylindrical cavity application to the storage of LNG’, *J. Pet. Sci. Eng.*, 71, pp. 126–132.
- 7) Zakaria, Z.B., Mustafa, A. and Mat, H. (2006) *Heat and mass transfer studies in liquefied petroleum gas storage operations*. Ph.D. dissertation, Univ. Technology Malaysia.
- 8) Shamekhi, S.S. and Ashouri, N. (2021) *Minimize evaporation losses by calculating boiloff gas in LPG storage tanks*. Gas Process. LNG. Available at: <http://www.gasprocessingnews.com>
- 9) Gbaarabe, B. and Sodiki, J.I. (2023) ‘Economic implication of boil-off gas generation in liquefied petroleum gas supply chain’, *Int. J. Mod. Res. Eng. Technol.*, 8(4), pp. 8–18.
- 10) Adom, E., Zahidul, S.I. and Ji, X. (2010) ‘Modelling of boil-off gas in LNG tanks: A case study’, *Int. J. Eng. Technol.*, 2(4), pp. 292–296.
- 11) Al Ghafri, S.Z.S., *et al.* (2021) ‘Advanced boil-off gas studies for liquefied natural gas’, *Appl. Therm. Eng.*, 189, pp. 15–21.
- 12) Cengel, Y., Boles, M. and Kanoglu, M. (2019) *Thermodynamics: An engineering approach*. 9th ed. New York: McGraw-Hill.
- 13) Usman, M.R. (2016) *Advanced chemical engineering thermodynamics*. Punjab: Inst. Chem. Eng. Technol.
- 14) Moran, M.J., Shapiro, H.N., Boettner, D.D., *et al.* (2011) *Fundamentals of Engineering Thermodynamics*. 7th ed. Hoboken: Wiley.
- 15) Bergman, T.L., Lavine, A.S., Incropera, F.P., *et al.* (2011) *Fundamentals of heat and mass transfer*. 7th ed. Hoboken: Wiley.
- 16) KTL (2019) *Catalogues of aboveground storage tanks and accessories for LPG*. Kada Technology Ltd. Available at: <http://kadatec.cz>